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Analysis of the Failure of the AUTEC TOTO II Deep Sea Moor and the Performance of its Cathodic Protection System

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ABSTRACT

This report contains background information on the design and installation of a wire rope three-point deep sea moor which was originally coated with a bituminous substance and the critical areas protected with a magnesium galvanic anode cathodic protection system designed by the Naval Research Laboratory. The report also describes the failure of the moor after 4 1/2 years' service and its subsequent salvage, and presents the results of a study of the corrosion pattern, proposes the cause of failure, and evaluates the performance of the cathodic protection system. Recommendations are presented for the protection of future moors and for possible research directed towards the understanding and prevention of failure of wire rope structures in sea water under conditions of static stress and of fatigue.

Three of the wire rope failures were associated with severe corrosion and the absence of bituminous coating. In two of the failures the bituminous coating was essentially absent but no severe corrosion was observed. There is some circumstantial evidence that the latter failures may have been caused by a ship mooring to the intermediate buoy which was not intended to be used for this purpose. All but one failure occurred 1350 to 2050 ft from the nearest active anode connections. One failure occurred 680 ft from an intended anode connection, but there is evidence that this particular anode was lost when the moor was installed. Some other major components of the moor probably received cathodic protection for as little as 9 to 12 months out of the approximate 54-months life of the moor. This was a result of a variety of problems associated with the replacement of the original anodes.

The results of the corrosive attack and the failure of the moor indicate that where long life is demanded for future moors the following steps should be taken:

(a) Provide a coating better than the bituminous substance used in the present moor.

(b) Provide cathodic protection as a secondary defense against corrosion. It is essential that cathodic protection be considered early in the design phase and provided throughout the life of the moor if it is to be effective. Scheduled inspections and replacement of consumed anodes are essential for prolonged trouble-free life of the structure. Where adequate power is available, impressed current systems should be considered to obviate the necessity of frequent anode replacement.

STATUS

This completes one phase of the program; work on other phases is continuing.

AUTHORIZATION

NRL Problem 63M04-02
Task No. S-4607-11894

INTRODUCTION

A fixed-position deep sea moor was needed by the Navy in conjunction with activities contemplated for the Tongue of the Ocean (TOTO) area.

A three-point moor, designated AUTEC TOTO II, was designed by the Bureau of Ships (now Naval Ship Systems Command) to meet the set requirements (1). The moor consisted of three legs positioned 120° apart. Each leg was comprised of the center buoy, a main buoy, and an intermediate buoy. Approximately 11,000 ft of 1 1/4-in. 6x19 filler wire (WSC), extra improved plow steel, galvanized, bituminous coated wire rope connected each main buoy to an anchor chain and anchor positioned on the sea floor. A 4,100-ft vertical riser beneath each intermediate buoy supported the wire rope between the main buoy and the anchor to form an upper and lower catenary. The risers were also 1 1/4-in.-diam wire rope except the upper 105 ft of each which consisted of 30 ft of 2 1/2-in. chain and 75 ft of 1 5/8-in.-diam wire rope. A schematic diagram showing the moor and a typical anchor leg is shown in Fig. 1.

After the moor design was completed and while materials were being procured, the Marine Corrosion Section of the Metallurgy Division, Naval Research Laboratory, was contacted concerning possible methods to extend the life of the moor beyond one to two years. NRL made an analysis of both the fundamental and operational aspects of providing cathodic protection to reduce corrosion on the AUTEC TOTO II moor (2,3,4). This analysis showed that it was not possible to protect the entire moor without a complete redesign (impractical), but that it would be possible to protect the critical junction points and the wire rope for about 600 ft from these junction points. It also appeared possible to protect the wire rope to a distance of several hundred feet up from the anchors. As the best available protection without redesign, NRL proposed to protect the critical areas of the moor with magnesium galvanic anodes. The necessary materials and equipment were procured and assembled at NRL and were later delivered to the vessels which were to lay the moor.

On 26-30 May 1962, the moor was laid in about 5400 ft of water in the TOTO. The late Mr. L. J. Waldron of NRL supervised the attachment of approximately 4400 lb of magnesium anodes to the moor at the locations shown in Fig. 1.

All anode arrays near the surface were designed to facilitate periodic examination and replacement, which was expected to be required after one to two years.

In September 1964 (approximately 28 months after the moor was installed), one anode which had been removed from the moor was returned to NRL. Inspection showed that only the core remained, indicating that the magnesium had been completely consumed and that anode replacement was required. On 13 November 1964, NRL was authorized to procure replacement anodes, and by early April 1965 they were assembled and ready for shipment to TOTO. The David Taylor Model Basin (DTMB) (now the Naval Ship Research & Development Center, Carderock) negotiated the contract for the installation of the replacement anodes and apparently experienced difficulties in letting the contract. This difficulty, plus other factors, delayed the actual shipment of the anodes until 18 October 1965.

According to "Negotiated Contract" N167-173(X)FBM issued by DTMB for installation of the replacement anodes and executed by the contracting officer on 19 August 1965, NRL was to coordinate (or direct) the technical aspects of the contractor's performance and was to inspect (at TOTO) the supplies and services provided by the contractor to assure conformance with the contract. Because NRL was not notified of the installation of the replacement anodes on 17-19 November 1965, the technical direction and inspection by NRL during anode replacement was not accomplished.

From study of an informal written report dated 29 November 1965 by the U.S. Navy Officer who worked with the contractor and from telephone conversations with the same officer, NRL concluded that it was unlikely that the replacement anodes had been installed according to anticipated replacement design.

FAILURE OF THE MOOR

In November 1966, about 4 1/2 years after the moor was installed, the 4100-ft vertical riser between the intermediate buoy and the ring which joined the upper and lower catenaries on the 150° leg parted at an estimated distance of 1700 ft below the intermediate buoy, or about 1700 ft from the nearest anode connection (5). In February 1967 a 48 1/2-ft section of the failed end of the riser was recovered. Parts of the recovered riser were sent to the Naval Applied Science Laboratory (NASL), and a 1-ft section was delivered to NRL on 8 May 1967. The failed section was observed to be severely corroded and had undergone an appreciable loss in breaking strength (6).

A similar riser beneath the 270° leg intermediate buoy failed about four months later (March 1967). A tug towed the buoy and riser section to the Atlantic Undersea Test and Evaluation Center (AUTEC) on the western shore of TOTO where the section was beached on 3 May 1967. Preliminary failure analysis made at AUTEC by the author disclosed that the riser had failed about 2580 ft below the intermediate buoy, or about 1520 ft from the nearest anode connection, and it was observed that replacement anodes had not been properly installed (7). Numerous samples were cut from the riser for study in the laboratory; the results of the study are reported herein.

SALVAGE OF THE MOOR

The failure of the two risers and the subsequent shifting of position of the remaining buoys led to a decision to salvage the remnants of the moor to remove the existing hazard to navigation. A contract was awarded to the Merritt Chapman & Scott Corporation, and their ship, the MV CABLE, was dispatched from Key West, Florida, to TOTO on 8 July 1967. Captain Henry Halboth joined the ship at TOTO as Salvage Master. The author was also aboard the salvage ship to obtain information and samples from the moor required to analyze the corrosion damage and performance of the cathodic protection system.

The CABLE arrived on site at 1240 hours on 10 July 1967 and moored to the main buoy on the 150° leg. All buoys except the 030° leg intermediate buoy were observed to lie in an approximate straight line bearing to the northwest. The first buoy to the northwest of the 150° leg main buoy was the center buoy, next the 030° leg main buoy, and last the 270° leg main buoy. The 030° leg intermediate buoy was far from the moor on a bearing of 352° from the 150° main buoy. The wind was from the east at 85°.

The position of the buoys indicated that the 030° anchor leg had failed, and the 030° main buoy had drifted into the span wire between the center buoy and the 270° leg main buoy. Later during the salvage operation it was discovered that both the upper and lower catenaries on the 030° leg had indeed failed, and the 030° intermediate buoy was adrift but was dragging about 700 ft of wire rope on the bottom thus slowing its rate of drift. The failure of the 030° leg apparently occurred prior to 12 May 1967 since on that date Naval Ship Engineering Center (NAVSEC) personnel observed that the buoys were in about the same relative position as reported above (8).

Salvage of the moor commenced on the afternoon of 11 July 1967. During the salvage operation, the following events occurred:

(a) The 270° lower catenary failed about 680 ft above the anchor chain. About 5950 ft of the upper catenary was on deck at the time, and the gage on the winch pulling on the catenaries indicated a stress on the rope of 39,000 lb before failure of the lower catenary which was reduced to 19,000 lb immediately after the failure. This indicates that the stress on the lower catenary at the point of failure was 20,000 lb when it failed.

(b) All remnants of the failed moor were salvaged except two anchors and anchor chains and part of the lower catenaries on the 030° and 270° legs.

Salvage was completed at 2220 hours on 20 July 1967.

EXAMINATION OF THE WIRE ROPE

Field Observations

The wire rope was observed visually as it was salvaged to determine the presence and location of broken wires and the appearance of the corrosion products. In addition, the wire rope was measured and tagged at preselected locations. Samples were cut from these locations for study in the laboratory. The remnants of anodes were also recovered for further study. All hardware items were checked for corrosion.

No multiple broken wires were noted near the anode connection points except that in a few instances some multiple wire breaks were noted at socket connections. However, some of these wires at sockets were observed to break when the sockets came over the bow roller of the CABLE at an angle and under high stress.

Multiple broken wires and a failure of the wire rope occurred 680 ft from the lower anode connection on the 270° lower catenary. The wire rope was severely corroded at and above the point of failure (Fig. 2). All other multiple broken wires and failures were at least 1000 ft from the nearest anode connection. Field observations relative to broken wires are given in Table 1.

The upper and lower catenaries on the 030° leg failed prior to salvage. Corrosion on the catenaries was not severe and is not believed to have been the cause of the failures. The 25-ft section of the upper catenary in which failure occurred had been twisted prior to failure. Color photographs are available at NRL (Code 6325) which show in detail the twist and failure. The lower catenary appeared to have kinked before or during failure (Fig. 3). It can be surmised that the 030° catenaries failed as a result of ships improperly mooring to the intermediate buoy rather than to the main buoy.

The 270° leg vertical riser failed about 2580 ft below the intermediate buoy. The appearance of the failed end is shown in Fig. 4.

The appearance of corrosion products on the wire rope components was generally gray-black near anode connections. Reddish-brown corrosion products gradually increased with distance from anode connections. At 1000-2000 ft from the anode connections about 100 percent of the visible wire surfaces were coated with reddish-brown corrosion products. The bulk of the corrosion products was located between adjacent strands. The density of the corrosion products appeared to increase with depth of water. This increase was particularly evident at depths greater than 2400 ft.

Laboratory Observations

Numerous samples (3 ft or longer) were cut from the wire ropes at the locations shown in Table 1. The technique used in the laboratory to evaluate the samples was as follows:

(a) An outer strand about 18-in. long was removed from each wire rope sample. The core strand was also removed where failures had occurred.

(b) The presence and amount of bituminous coating on the strands was determined visually.

(c) The strands were soaked in mineral spirits, then rinsed in trichloroethylene to remove the bituminous coating.

(d) The cleaned strands were examined at 7X magnification under a stereo-microscope to estimate the percentage of the zinc coating still present. Hydrochloric acid (to cause hydrogen ebullition) was used as a further spot check on questionable areas. The same technique was used to estimate the percentage of zinc remaining on an individual outer wire from each strand.

(e) Alternate outer wires (six per strand) were removed from each strand, except that it was necessary to remove all (12) outer wires from core strands from the 030° leg because adjacent outer wires were of different diameters. This procedure is in contrast to that used for the outer wires evaluated from other core strands, which had the same diameters.

(f) The removed outer wires and remaining wires in strands were recleaned in trichloroethylene. Corrosion products and zinc were then removed by immersing the wires in concentrated hydrochloric acid inhibited with 40 g/l antimony trioxide at room temperature. The wires were rinsed in water and coated with a rust-preventive compound.

(g) The inner wires of the strands were viewed at 7X magnification to determine the presence and extent of corrosion pits, and the remaining outer wires on the strands were checked for cracked wires and mechanical damage.

(h) The removed outer wires from the strands were viewed at 7X magnification to determine the presence of broken or cracked wires and mechanical damage. The minimum diameter of each outer wire was then determined to the nearest mil using a micrometer.

The results of the determination of minimum diameter of outer wires are shown in Table 1, together with the laboratory data concerning broken wires, pitting of inner wires, and the presence of mechanical damage. Table 1 relates these data to the approximate depth of water, distance from the nearest anode connection, total anode consumption, and field observations relative to broken wires.

The data show that broken wires were observed in the field on the 150° leg lower catenary, but none were found on the small laboratory samples removed from the catenary. Field and laboratory observations of broken wires were in good agreement in all other instances.

Mechanical damage noted in the table refers to slight plastic deformation of outer wires on strands. The damage was noted on the 150° upper and lower catenaries and the 270° upper catenary. The cause could not be determined.

The minimum diameter of outer wire data from Table 1 are plotted in Figs. 5, 7, and 9 and are related to the locations of anodes, approximate depth of water, and locations of wire rope failures.

Figure 5 shows that the average minimum diameter of outer wires from the upper catenaries ranged from 53 to 77 mil. The wires having smaller residual diameters were located about 1000 ft from the upper anodes, and those having larger residual diameters were at the lower ends of the catenaries near the 400-lb anode connections. The 030° leg upper catenary twisted and failed at the location shown in the figure. It is apparent that the point of failure was not associated with minimum wire diameter or the point of highest natural stress since both would be towards the upper end of the catenary. The appearance of failed ends of wires from the 030° leg upper catenary is shown in Fig. 6.

The average minimum diameter of the outer wires of the lower catenary ranged from 0 to 81 mil as shown in Fig. 7. The outer wires from the 270° lower catenary at the point of failure were completely severed by corrosion. Severe corrosion was also noted on the core strand of the 270° lower catenary at this point. Severe reduction of the diameter of the outer wires was not noted on the 030° lower catenary which failed or on the 150° lower catenary. This suggests that the 400-lb anode at the lower end of the 270° lower catenary was lost when the moor was laid and thus permitted severe corrosion to occur. Another significant factor which contributed to the severe corrosion of the 270° lower catenary was the relatively poor coverage of bituminous coating on the strands (Table 2). The appearance of failed ends of wires from the 030° leg lower catenary is shown in Fig. 8.

The contrast in performance of the risers beneath the intermediate buoys of the 030° and 270° legs is shown in Fig. 9. Data from the failed 150° leg riser are not shown because samples were not available. It is evident from Fig. 9 that the diameters of outer wires from the 030° leg riser were not drastically reduced, but the opposite effect was noted for the 270° leg riser which failed because of severe corrosion. The only apparent explanation for the divergent behavior of risers is that the 030° leg riser was relatively well protected by the bituminous coating (Table 2). A cross section of the 270° leg riser approximately 50 ft above the failure is shown in Fig. 10, and the appearance of failed ends of wires from this riser is shown in Fig. 11.

Table 2 shows that the bituminous coating on the wire ropes ranged from 0 to 100 percent coverage. All failures of the wire ropes were associated with almost complete absence of bituminous coating. The variability of coverage by the bituminous coating suggests that either the wire ropes were not uniformly coated during manufacture, or the coating leaked out of some sections of wire rope before the moor was laid. It was observed during salvage of the moor that the heat of the sun was sufficient to cause melting and leakage of the coating. Because the galvanizing is a sacrificial coating, the presence of zinc (galvanize) on strands and wires also ranged from 0 to 100 percent, with the higher percentage generally being associated with good coverage by the bituminous coating.

PERFORMANCE OF THE CATHODIC PROTECTION SYSTEM

The magnesium anode cathodic protection system was expected to do the following:

(a) Protect the moor at critical junctures where continuous rubbing of the surfaces might be expected to continuously remove corrosion products and thereby promote corrosion.

(b) Protect the wire rope to about 600 ft from the point of connection to the anodes provided the bituminous coating used on the wire rope met the minimal conditions used to specify a "very poor" coating.

(c) Extend the service life of the moor beyond that of an unprotected moor.

The overall effectiveness of the cathodic protection system cannot be fully determined for reasons which will become apparent later in this report. However, we can report that:

(a) No severe corrosion of hardware was observed at critical junctures, although some broken wires were observed at sockets, probably caused by severe bending stresses during salvage.

(b) All but one of the wire rope failures occurred 1350 to 2050 ft from the nearest anode connection. One failure occurred 680 ft from an anode connection, but in this instance there is evidence that the anode near the failure was probably lost when the moor was laid.

(c) The life of the moor was 4 1/2 years.

The original anodes which were installed when the moor was laid - particularly those installed to protect the upper ends of the risers and the intermediate buoys - were consumed more rapidly than anticipated. Calculations based on the rate of consumption of replacement anodes at these locations indicate that the original three 60-lb anodes beneath each intermediate buoy were consumed within 9 to 12 months after the moor was laid. These and the other consumed anodes were not replaced until November 1965, or 30 to 33 months too late to insure continuous effectiveness from the cathodic protection system. By this time the 400-lb anodes at the lower ends of the riser were probably consumed, and they were not replaced. From the post-mortem observations and calculations it appears that the failed risers were cathodically protected for only 9 to 12 months of their 54-month life.

There are strong indications that the November 1965 replacement of the consumed anodes was accomplished by divers who apparently were not aware of the technical requirements of providing low resistance electrical contacts between the anode strings and the moor. This

was evident from the fact that they looped the insulated conductors from the strings through shackles which they attached to the moor at convenient locations. Fortunately the insulation on the conductors broke under the weight of the anodes and a degree of electrical contact was established which permitted the anodes to function. The divers lost all 400-lb replacement anodes when they apparently allowed the anodes to free fall down the risers. This was evident from the fact that the sheared eyebolts (minus the 400-lb magnesium anodes) were located at the rings 115 ft below the intermediate buoys.

Since all available replacement anodes were salvaged, it was possible to obtain data concerning performance of the anodes which may be useful in future designs of cathodic protection systems for wire rope structures. One original 400-lb anode was also salvaged from the junction of the 150° lower catenary and the anchor chain. This anode is of particular interest because it functioned continuously for approximately five years at low temperature and high pressure at a depth of 5400 ft. The performance data for the anodes are summarized in Table 3.

The estimated anode current densities ranged from 161 to over 550 ma/sq ft for the 120-lb anodes; the density was 445 ma/sq ft for the 400-lb anode. These current densities are based on the original surface area of the anodes and an assumed anode efficiency of 500 amp-hr/lb. The corrosion patterns developed on some of the anodes operating at various current densities are shown in Fig. 12.

SUMMARY AND RECOMMENDATIONS

1. A three-point wire rope deep sea moor was laid in the Tongue of the Ocean in 5400 ft of water on 26-30 May 1962. The moor was protected from corrosion by a bituminous coating and critical areas were protected with a magnesium galvanic anode cathodic protection system designed by NRL. The moor failed after about 4 1/2 years. It was then salvaged and samples of the wire rope and the anodes were obtained for a study of the cause of failure and the performance of the cathodic protection system.

2. Failure of two 1 1/4-in.-diam wire rope risers beneath the intermediate buoys and failure of the 270° lower catenary were associated with severe corrosion and the absence of bituminous coating on the wire ropes. Corrosion of the other lower catenaries was not severe which leads us to speculate that the anode was probably lost off the lower end of the 270° lower catenary when the moor was laid. Also, the coverage of the bituminous coating was better on the riser and catenaries which did not fail.

3. The failure of the 1 1/4-in.-diam wire rope upper and lower catenaries on the 030° leg was associated with twists and kinks in the catenaries rather than with severe corrosion. This suggests that these failures may have occurred as a result of a ship improperly mooring to the 030° leg intermediate buoy rather than to the main buoy.

4. The fractured ends of wires from the moor showed a variety of failure appearances. These included transverse, longitudinal, and diagonal cracking, and general corrosion. Research should be directed toward the understanding and prevention of the failure of wire rope in sea water under conditions of static stress and of fatigue.

5. A general reduction in the diameter of outer wires of the strands (other than core strands) was noted on all wire rope components. The diameter of outer wires from core strands was reduced at or near points of failure. The amount of reduction in the diameter of outer wires did not appear to be related to the depth of the water where the samples were obtained.

6. The coverage of bituminous coating on the wire ropes ranged from 0 to 100 percent indicating that the coating was either not uniformly applied during manufacture or leaked out of some sections before the moor was laid. During salvage, heat from the sun was observed to be sufficient to melt the coating. Since coatings should perform vital functions in protecting wire ropes, a more durable and protective coating should

be obtained or developed for future moors. To assure coating of outer wires, equipment should be developed as required to automatically apply a final coating to the wire rope as it passes from the ship into the water.

7. The magnesium anode cathodic protection system was expected to protect the moor at critical junctures, protect the wire rope for approximately 600 ft from anode connections, and extend the life of the moor. This study of the failed moor revealed that there was no apparent severe corrosion of hardware at critical junctures, although some broken wires were observed at sockets; all but one wire rope failure occurred at a distance of 1350 to 2050 ft from anode connections. There is evidence that in one failure (approximately 680 ft from an anode) the anode was probably lost when the moor was laid. The life of the moor was 4 1/2 years.

8. The true effectiveness of the cathodic protection system could not be fully determined because of its intermittent operation resulting from a variety of problems associated with the replacement of anodes after the original anodes were consumed. It was estimated that the risers which failed had cathodic protection for only 9 to 12 months out of this 54-month life because of these problems.

9. All available replacement anode strings were salvaged. One original 400-lb anode was salvaged. This anode operated continuously for 5.12 years at low temperature and high pressure at a depth of about 5400 ft. Data were obtained relative to the performance of these anodes which should be useful if the design of another galvanic anode system for a wire rope structure is required.

10. Cathodic protection should be considered early in the design of future deep sea moors, and attachment points for installing anodes should be provided at suitable intervals (probably not over 1,000 ft apart), or sheathing materials better than the bituminous coating must be applied to enable cathodic protection to work over a longer distance.

11. Cathodic protection systems on future moors should include scheduled inspections, and consumed anodes should be replaced in a timely manner so that the moor will not be without protection for long intervals as was the TOTO II moor.

12. The means for replacing consumed anodes should be provided in the initial design of future moors.

13. When consumed anodes are replaced on future moors, the installation of the replacement anodes should only be accomplished under the technical supervision of personnel who understand the critical requirements of the cathodic protection system.

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TABLE 1

RESULTS OF THE EVALUATION OF WIRE ROPE FROM THE TOTO II DEEP SEA MOOR AND RELATED DATA

Leg, Position, and Wire Rope Diameter	Specimen Identification	Distance from Reference (ft)	Approximate Depth of Water (ft)	Distance from Nearest Anode Connection (ft)	Diameter of Outer Wires (mils) Minimum	Diameter of Outer Wires (mils) Typical Maximum	Microscopic Examination Broken Wires	Microscopic Examination Pitting of Inner Wires	Microscopic Examination Mech. Damage	Total Anode Consumption (lb)	Some Field Observations
030° Upper Catenary 1 1/4-in. diameter	3	10	115	10	57	84	N	N	N	360+536=896	First fishhook was noted 2375 ft from ring beneath main buoy. Multiple broken wires were observed from 2750 to 6000 ft from the ring.
	7	1000	900	1000	53	84	N	N	N		
	6	2000	1650	2000	54	84	N	N	N		
	5	3000	2350	3000	73	84	N	N	N		
	4	4912	3475	2088	70	84	N	N	N		
	4-Failure	4950	3475	2050	64	84	Yes	S	N		
	4-Core	4950	3475	2050	52/79	77/102	Yes	S	N		
	16-Failure	4950	3475	2050	60	84	Yes	S	N		
	16-Core	4950	3475	2050	50/84	77/102	Yes	S	N		
	15	5000	3500	2000	68	84	Yes	N	N		
	14	6000	3850	1000	65	84	Yes	N	N		
	9	7000	4100	10	74	84	N	N	N	400	
150° Upper Catenary 1 1/4-in. diameter	43	10	115	10	62	83	N	N	N	360+474=834	No broken wires noted.
	48	500	500	500	61	83	N	N	N		
	47	1000	900	1000	55	83	N	N	Yes		
	46	2000	1650	2000	67	83	N	N	Yes		
	45	3000	2350	3000	66	83	N	N	Yes		
	44	4000	3000	3700	67	83	N	N	Yes		
	49	5000	3500	2700	67	83	N	N	Yes		
	50	6000	3850	1700	64	83	N	N	Yes		
	53	7000	4075	700	70	83	N	N	N		
	57	7700	4100	10	77	83	N	N	N	400	
270° Upper Catenary 1 1/4-in. diameter	21	10	115	10	65	83	N	N	N	360+411=771	Multiple broken wires were present near upper socket but were observed to break when socket and ring came over bow roller of ship. No other broken wires noted.
	25	1000	900	1000	59	83	N	N	Yes		
	24	2000	1650	2000	64	83	N	N	Yes		
	23	3000	2350	3000	64	83	N	N	N		
	22	4000	3000	3400	72	83	N	N	Yes		
	40	5000	3500	2400	67	83	N	N	Yes		
	39	6000	3850	1400	69	83	N	N	Yes		
	38	7000	4075	400	48	83	N	N	Yes		
	26	7400	4100	10	76	83	N	N	N	400	
030° Lower Catenary 1 1/4-in. diameter	10	10	4100	10	74	84	N	N	N	400 (Previously Listed)	No broken wires noted except at point of failure.
	11	1000	4700	1000	70	84	N	N	N		
	12	1330	4800	1330	63	84	N	N	N		
	12-Failure	1350	4600	1350	62	84	Yes	S	N	Unknown (Not Salvaged)	
	12-Core	1350	4800	1350	62/88	77/(103)	Yes	S	N		
150° Lower Catenary 1 1/4-in. diameter	54	10	4100	10	73	85	N	N	N	400 (Previously Listed)	Isolated broken wires started 1150 ft from upper ring and continued to 1200 ft. Multiple broken wires 1200 ft to 2300 ft. Breaks were very numerous between 1300 and 2200 ft. No breaks noted between 2925 ft and the anchor chain at 3600 ft.
	56	1000	4700	1000	65	85	N	N	Yes		
	55	1500	4900	1600	72	85	N	N	N		
	58	3000	5350	600	77	85	N	N	N	368	
	59	3600	5400	10	81	85	N	N	N		
270° Lower Catenary 1 1/4-in. diameter	31	10	4100	10	61	81	N	N	N	400 (Previously Listed)	Multiple broken wires near socket. Isolated fishhooks to 1500 ft from ring. Multiple broken wires from 1500 ft from ring to 2870 ft (point of failure).
	27	1000	4700	1000	48	81	N	N	N		
	29	2000	5100	1550	48	81	Yes	N	N		
	30	2837	5300	713	36	81	Yes	S	N		
	30X	2849	5300	701	37	81	Yes	S	N		
	30X-Failure	2870	5300	680	0	81	Yes	N	N		
	30X-Core	2870	5300	680	24	85	Yes	N	N	Unknown (Not Salvaged)	
030° Vertical Riser (Beneath Intermediate Buoy) 1 1/4-in. diameter	17	120	120	120	67	84	N	N	N	180+402=582	Isolated broken wires started 3315 ft below buoy and continued to 4040 ft where multiple broken wires were noted near the socket.
	20	1100	1100	1100	61	84	N	N	N		
	19	2100	2100	1940	64	84	N	N	N		
	18	3100	3100	940	67	84	Yes	N	N	400 (Previously Listed)	
	13	4040	4040	10	62	84	Yes	N	N		
150° Vertical Riser (Beneath Intermediate Buoy) 1 1/4-in. diameter											Failed an estimated 1100 ft below the intermediate buoy 4-1/2 years after installation. Not salvaged except for one specimen previously reported (references 4 and 5).
270° Vertical Riser (Beneath Intermediate Buoy) 1 3/8-in. diameter	1R	40	40	40	93	103	N	T	N	180+306=486	No broken wires noted.
	2R	92	92	92	85	103	N	T	N		
270° Vertical Riser (Beneath Intermediate Buoy) 1 1/4-in. diameter	3R	120	120	120	59	80	N	N	N	486 (Previously Listed)	First fishhook was noted 1275 ft below intermediate buoy and multiple broken wires were observed between 1350 ft and 3060 ft below the buoy and also near the socket at the lower ring.
	4R	230	230	230	63	80	N	N	N		
	5R	330	330	330	73	80	N	N	N		
	6R	630	630	630	68	80	N	N	N		
	7R	930	930	930	54	80	N	N	N		
	8R	1230	1230	1230	56	80	N	N	N		
	9R	1350	1350	1350	52	80	N	N	N		
	10R	1530	1530	1530	55	80	N	N	N		
	11R	1830	1830	1830	54	80	N	N	N		
	12R	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]		

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1 1/4-in. diameter	11	1000	4700	1000	70	85	N	N	N	(Previously Listed)	point of failure.
	12	1330	4800	1330	63	[illegible]	N	N	N		
	12-Failure	1350	4800	1350	62	[illegible]	Yes	S	N		
	12-Core	1350	4800	1350	62/88	[illegible]	Yes	S	N	Unknown (Not Salvaged)	
150° Lower Catenary 1 1/4-in. diameter	54	10	4100	10	73	85	N	N	N	400 (Previously Listed)	Isolated broken wires started 1150 ft from upper ring and continued to 1200 ft. Multiple broken wires 1200 ft to 2300 ft. Breaks were very numerous between 1300 and 2200 ft. No breaks noted between 2925 ft and the anchor chain at 3600 ft.
	56	1000	4700	1000	65	85	N	N	Yes		
	55	1600	4900	1600	72	85	N	N	N		
	58	3000	5350	600	77	85	N	N	N	388	
	59	3600	5400	10	81	85	N	N	N		
270° Lower Catenary 1 1/4-in. diameter	31	10	4100	10	61	81	N	N	N	400 (Previously Listed)	Multiple broken wires near socket. Isolated fishhooks to 1500 ft from ring. Multiple broken wires from 1500 ft from ring to 2870 ft (point of failure).
	27	1000	4700	1000	48	81	N	N	N		
	29	2000	5100	1550	48	81	Yes	N	N		
	30	2837	5300	713	36	81	Yes	S	N		
	30X	2849	5300	701	37	81	Yes	S	N		
	30X-Failure	2870	5300	680	0	81	Yes	N	N		
	30X-Core	2870	5300	680	24	85	Yes	M	N	Unknown (Not Salvaged)	
030° Vertical Riser (Beneath Intermediate Buoy) 1 1/4-in. diameter	17	120	120	120	67	84	N	N	N	180+402=582	Isolated broken wires started 3315 ft below buoy and continued to 4040 ft where multiple broken wires were noted near the socket.
	20	1100	1100	1100	61	84	N	N	N		
	19	2100	2100	1940	64	84	N	N	N		
	18	3100	3100	940	67	84	Yes	N	N		
	13	4040	4040	10	62	84	Yes	N	N	400 (Previously Listed)	
150° Vertical Riser (Beneath Intermediate Buoy) 1 1/4-in. diameter											Failed an estimated 1700 ft below the intermediate buoy 4-1/2 years after installation. Not salvaged except for one specimen previously reported (references 4 and 5).
270° Vertical Riser (Beneath Intermediate Buoy) 1 3/8-in. diameter	1R	40	40	40	93	103	N	T	N	180+306=486	No broken wires noted.
	2R	92	92	92	85	103	N	T	N		
270° Vertical Riser (Beneath Intermediate Buoy 1 1/4-in. diameter	3R	120	120	120	59	80	N	N	N	486 (Previously Listed)	First fishhook was noted 1275 ft below intermediate buoy and multiple broken wires were observed between 1530 ft and 3080 ft below the buoy and also near the socket at the lower ring.
	4R	230	230	230	63	80	N	N	N		
	5R	330	330	330	73	80	N	N	N		
	6R	630	630	630	68	80	N	N	N		
	7R	930	930	930	54	40	N	N	N		
	8R	1230	1230	1230	56	80	N	N	N		
	9R	1350	1350	1350	52	80	N	N	N		
	10R	1530	1530	1530	55	80	N	N	N		
	11R	1830	1830	1830	54	80	N	N	N		
	12R	2130	2130	1970	44	80	N	N	N		
	13R	2430	2430	1670	51	80	Yes	N	N		
	14R	2480	2480	1620	57	80	Yes	N	N		
	15R	2530	2530	1570	54	80	N	N	N		
	16R-Failure	2580	2580	1520	40	80	Yes	S	N		
	16R-Core	2580	2580	1520	52	88	Yes	S	N		
	28-Failure	2580	2580	1520	33	80	Yes	S	N		
	28-Core	2580	2580	1520	58	88	Yes	T	N		
	28	2595	2595	1505	48	80	Yes	M	N		
	32	4100	4100	10	59	80	N	N	N	400 (Previously Listed)	
030° Span Wire 1 1/4-in. diameter	35	10	115	10	66	84	N	N	N	360+235=595	No broken wires noted.
	1	500	115*	500	63	84	N	N	N		
	2	1000	115	10	64	84	N	N	N	896 (Previously Listed)	
150° Span Wire 1 1/4-in. diameter	42	10	115	10	59	83	N	N	N	594 (Previously Listed)	No broken wires noted.
	36	500	115*	500	73	83	N	N	N		
	8	1000	115	10	63	83	N	N	N	834 (Previously Listed)	
270° Span Wire 1 1/4-in. diameter	41	10	115	10	61	83	N	N	N	594 (Previously Listed)	No broken wires noted.
030° Vertical Riser Beneath Main Buoy 1 3/8-in. diameter	51	35	35	70	75	103	N	N	N		No broken wires noted.
	52	105	105	10	80	102	N	N	N	896 (Previously Listed)	

NOTES:

1. Distances along the span wires are relative to the flounder plate as zero reference.
2. Distances along the 030° vertical riser beneath the main buoy are relative to the main buoy as zero reference.
3. Distances along the upper catenaries are relative to the ring located 115 ft below each main buoy as zero reference.
4. Distances along the lower catenaries are relative to the ring located approximately 4100 ft below each intermediate buoy as zero reference.
5. Distances along the vertical risers beneath the intermediate buoys are relative to each intermediate buoy as zero reference.
6. Minimum diameter indicated is the average diameter of six outer wires taken from a strand of each specimen, except wires from two strands (one, the core strand) were measured where failure had occurred. Note that two diameters of the outer wires were present in the core strands from the 0°/° leg whereas only one diameter of the outer wires was noted in the core strands from the other legs.
7. At least six outer wires from a strand from each specimen were viewed at 7X magnification to determine presence of broken (or cracked) wires or mechanical damage (plastic deformation) or both. The inner wires from the same strands were viewed at the same magnification to determine the presence of corrosion pits. Symbols used: N = None observed; T = Trace; S = Slight; M = Moderate; and H = Heavy (or severe).
8. Anode consumption is listed for both original and replacement anodes.
9. Observations relative to broken wires were made in the field during and after salvage of the moor. Distances indicated are relative to the same reference as those listed in Column 3. Correlation between field and laboratory observations of broken wires are generally good except in the case of the 150° lower catenary where numerous broken wires were noted in the field but none were observed during microscopic evaluation in the laboratory.

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TABLE 2

RESULTS OF THE EVALUATION OF BITUMINOUS COATING AND ZINC (GALVANIZE) ON WIRE ROPE FROM THE TOTO II DEEP SEA MOOR

Leg, Position, and Wire Rope Diameter	Specimen Identification	Bituminous Coating on Strands: In Crevice	Bituminous Coating on Strands: Out Crevice	Zinc on Strands: In Crevice	Zinc on Strands: Out Crevice	Zinc on Individual Wires: In Crevice	Zinc on Individual Wires: Out Crevice
030° Upper Catenary 1 1/4-in. diameter	3	M-S	N	M	S	H	S
	7	M-H	T	M	T	H	T
	6	M-S-T	N	S	N	M	N
	5	M	T	S	N	H	N
	4	T	T	T	N	S-T	N
	4-Failure	N-T	N	N	N	T-N	N
	4-Core	N-T	-	N	-	N	N
	16-Failure	T-N	N	N	N	S	N
	16-Core	T-N	-	N	-	S-N	N
	15	S-N	N	N	N	M-S	N
	14	S	N-T	T	T-N	H	T-N
	9	S-M	T	T	T	H	T
150° Upper Catenary 1 1/4-in. diameter	43	M	N	S-M	N	H	T
	48	H	T	S	T	H	T-S
	47	M	T	T-S	N-T	H	M
	46	M-H	T-S	S	T-S	H	T-N
	45	M-H	S	T-S	N-T	H	T
	44	M	T-S	N-T	N-T	H	T
	49	M	T-S	T	T	H	T-N
	50	S-M	S	T	T	H	T-N
	53	M	S	S	N-T	H	T-N
	57	M-S	S	T	N	H	S
270° Upper Catenary 1 1/4-in. diameter	21	S-M	T	M	T	H	N
	25	M	T	S	T	M	N
	24	M	T-N	S	N	M	S
	23	N-S	T	T	N	N	N-T
	22	M	S	S	H	H	T
	40	M	T	N-T	N-T	H	T
	39	H	T-S	T-S	T-S	H	T
	38	M-H	M	T	T	H	T
	26	M-H	S	M	M	H	T
030° Lower Catenary 1 1/4-in. diameter	10	M	S	S	T	H	T
	11	M-H	S	S	T	H	N
	12	T	N	N	N	S	T
	12-Failure	N-T	N	N	N	N	N
	12-Core	N-T	-	N	-	N	N
150° Lower Catenary 1 1/4-in. diameter	54	M-H	N-T	T	T	H	N
	56	S	T	N	N	M	T-N
	55	M-H	M	T-S	T	H	S
	58	M-H	M	T-S	T-S	H	S
	59	S-H	N	M-H	N	H	S
270° Lower Catenary 1 1/4-in. diameter	31	N	N	T	T	T-S	N
	27	T-S	N-T	T	N	S	N
	29	T-S	N-T	T	N	T	N
	30	N	N	N	N	N	N
	30X	N	N	N	N	N	N
	30X-Failure	N	N	N	N	-	-
	30X-Core	N	-	N	-	N	N
030° Vertical Riser (Beneath Intermediate Buoy) 1 1/4-in. diameter	17	M	N	M	S	H	T
	20	H	T	M	T	H	M
	19	H	S	S	T	H	N
	18	H	S	S	T	H	T
	13	M	N	T	N	M	T-N
150° Vertical Riser (Beneath Intermediate Buoy) 1 1/4-in. diameter	None						
270° Vertical Riser (Beneath Intermediate Buoy) 1 5/8-in. diameter	1R	S-M	N	S	N	S-H	T
	2R	S-M	N	S	N	M-H	T
270° Vertical Riser (Beneath Intermediate Buoy) 1 1/4-in. diameter	3R	S	N	T-N	N	M	T
	4R	S	N	T-N	N	S-M	T
	5R	S	N	T-N	N	M-H	T
	6R	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]	[illegible]

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030° Lower Catenary 1 1/4-in. diameter	40	M	T	N-T	N-T	M	T
	39	H	T-S	T-S	T-S	H	T
	38	M-H	M	T	T	H	T
	26	M-H	S	M	M	H	T
	10	M	S	S	T	H	T
	11	M-H	S	S	T	H	N
	12	T	N	N	N	S	T
	12-Failure	N-T	N	N	N	N	N
	12-Core	N-T	-	N	-	N	N
150° Lower Catenary 1 1/4-in. diameter	54	M-H	N-T	T	T	H	N
	56	S	T	N	N	M	T-N
	55	M-H	M	T-S	T	H	S
	58	M-H	M	T-S	T-S	H	S
	59	S-M	N	M-H	N	H	S
270° Lower Catenary 1 1/4-in. diameter	31	N	N	T	T	T-S	N
	27	T-S	N-T	T	N	S	N
	29	T-S	N-T	T	N	T	N
	30	N	N	N	N	N	N
	30X	N	N	N	N	N	N
	30X-Failure	N	N	N	N	-	-
	30X-Core	N	-	N	-	N	N
030° Vertical Riser (Beneath Intermediate Buoy) 1 1/4-in. diameter	17	M	N	M	S	H	T
	20	H	T	M	T	H	M
	19	H	S	S	T	H	N
	18	H	S	S	T	H	T
	13	M	N	T	N	M	T-N
150° Vertical Riser (Beneath Intermediate Buoy) 1 1/4-in. diameter	None						
270° Vertical Riser (Beneath Intermediate Buoy) 1 5/8-in. diameter	1R	S-M	N	S	N	S-H	T
	2R	S-M	N	S	N	M-H	T
270° Vertical Riser (Beneath Intermediate Buoy) 1 1/4-in. diameter	3R	S	N	T-N	N	M	T
	4R	S	N	T-N	N	S-M	T
	5R	S	N	T-N	N	M-H	T
	6R	S	N	T-N	N	M-H	T
	7R	S	N	N	N	S-M	N
	8R	S	N	T-N	N	M-H	T
	9R	T	N	N	N	S-M	T-N
	10R	M	N	T-N	N	S-M	S-N
	11R	M	N	T-N	N	S-M	T
	12R	T	N	N	N	M	N
	13R	T-N	N	N	N	S	N
	14R	T-S	N	N	N	S	N
	15R	T-S	N	N	N	S	N
	16R-Failure	N	N	N	N	T	N
	16R-Core	N	-	N	-	S-N	N
	28-Failure	N-T	N	N	N	N	N
	28-Core	N-T	-	N	-	T-N	N
	28	N-T	N	N	N	T	N
	32	N-T	T	T	N	T	N
030° Span Wire 1 1/4-in. diameter	35	-	-	M-H	S	H	T
	1	H	N	M	S	H	T
	2	M-S	N	M	N	H	T
150° Span Wire 1 1/4-in. diameter	42	M-H	S	S-M	T-S	H	S
	36	M-H	N	M-H	S-M	H	T-S
	8	M-H	N	M	T	H	S
270° Span Wire 1 1/4-in. diameter	41	M-S	T	S-M	T-S	H	T-S
030° Vertical Riser (Beneath Main Buoy) 1 5/8-in. diameter	51	M	N	S-M	N-T	M-H	T-N
	52	S	N	S	N-T	M	T

NOTES:

1. One outer strand was removed from each specimen (except the core strand was also removed from failed specimens) so that the presence of bituminous coating could be determined. "In crevice" refers to the crevice formed between adjacent strands. In the case of core strands all the outer wires are considered "in crevice". Significance of symbols:

   N = No coating present
   T = Trace < 10 percent coverage
   S = Slight: ~ 30 percent coverage
   M = Moderate: ~ 70 percent coverage
   H = Heavy: ~ 100 percent coverage

   Multiple symbols indicate variable degrees of coverage existing along the specimen. The first symbol in the group indicates the predominant condition.

2. The presence of zinc (galvanize) on a strand from each specimen (also the core strand where failed) was determined by microscopic and chemical means. The term "in crevice" and the symbols used have the same significance as in Note No. 1.

3. The presence of zinc on individual outer wires from the strands were determined as in Note No. 2. Symbols used have the same significance as above but the term "in crevice" refers to the crevice formed between the individual outer wire and adjacent wires including inner wires in the strand.

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TABLE 3

DETAILS OF PERFORMANCE OF MAGNESIUM ANODES FROM THE TOTO II DEEP SEA MOOR[1]

Location on Moor[2]	Anode No.	Approximate Initial Weight[3] (lb)	Final Weight (lb)	Weight Loss (lb)	Total Weight Loss (lb)	Estimated Anode Current Density[4] (ma/sq ft)	Average Current to the Moor[5] (amp)
Beneath Center Buoy	37-1 (Upper)	120	71	49	225	226	8.1
	-2	120	82	38		175	
	-3	120	84	36		166	
	-4	120	83	37		171	
	-5	120	85	35		161	
	-6	120	80	40		186	
Beneath 030° Main Buoy	33-1 (Upper)	120	0	120	536	>550	15.6
	-2	120	20	100		461	
	-3	120	33	87		401	
	-4	120	37	83		383	
	-5	120	48	72		332	
	-6	120	46	74		342	
Beneath 150° Main Buoy	XX-1 (Upper)	120	0	120	474	>550	16.4
	-2	120	18	102		465	
	-3	120	51	69		318	
	-4	120	61	59		272	
	-5	120	61	59		272	
	-6	120	55	65		250	
Beneath 270° Main Buoy	34-1 (Upper)	120	45	75	412	348	14.2
	-2	120	48	72		332	
	-3	120	50	70		325	
	-4	120	55	65		300	
	-5	120	53	67		309	
	-6	120	[illegible]	62		286	
Beneath 030° Intermediate Buoy	X-1 (Upper)	120	39	81	403	374	13.9
	-2	120	50	70		323	
	-3	120	55	65		320	
	-4	120	64	56		268	
	-5	120	55	65		300	
	-6	120	54	66		304	
Beneath 150° Intermediate Buoy	Not Salvaged	-	-	-	-	-	-
Beneath 270° Intermediate Buoy	1 (Upper)	120	60	60	308	315	12.1
	2	120	65	55		289	
	3	120	74	46		242	
	4	120	73	47		247	
	5	120	71	49		258	
	5	120	69	51		268	
At the Junction of the 150° Lower Catenary and the Anchor Chain	60	400	12	388	388	445	4.3

NOTES:

1. All original 60-lb anodes were totally consumed. All but one (see table) of the original 400-lb anodes were totally consumed except perhaps those at the junctions of the 030° and 270° lower catenaries with the anchor chains (these anodes were not salvaged). All salvaged anodes are included in the above table. Replacement 400-lb anodes are not included because they were lost at the time of replacement. Composition of anodes was to MIL-A-21412.

2. Replacement anodes were installed on 17-19 November 1965 and were salvaged on 11-15 July 1967 (about 604 days [1.65 years] exposure) except those beneath the 270° intermediate buoy were salvaged on 3 May 1967 (about 530 days [1.45 years] exposure).

   The 400-lb anode at the junction of the 150° lower catenary and the anchor chain were salvaged after 5.12 years exposure.

3. The 120-lb replacement anodes original dimensions were 36 x 7 x 7 in., and the 400-lb anodes were 60 x 10 x 10 in.

4. Calculation of anode current density: (ma/sq ft)

$$C.D. = \frac{5 \times 10^5\ W}{8{,}760\ TA}$$

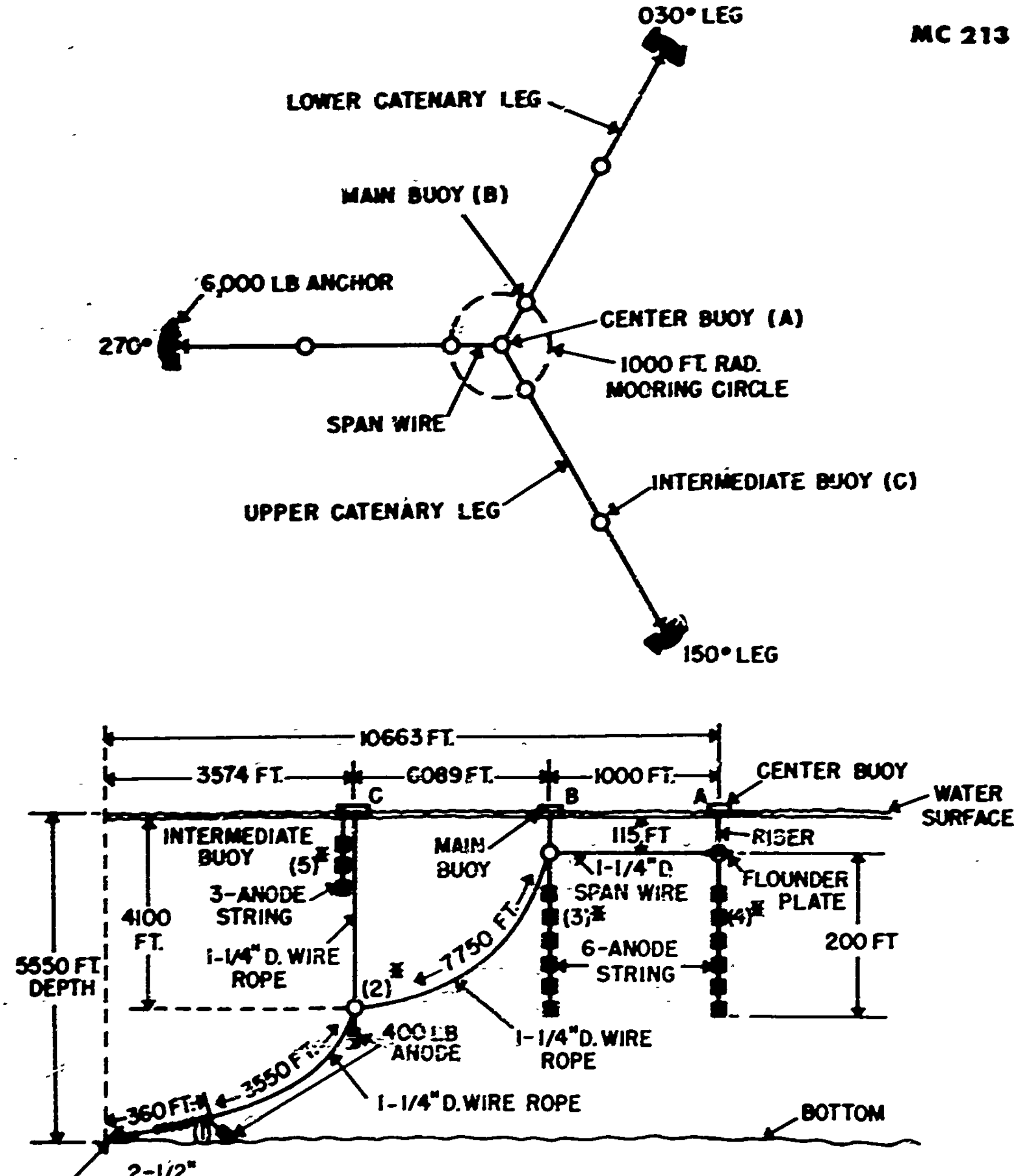
where 5×10^5 = Assumed ma-hr/lb produced by the anode
W = Weight lost by the anode (lb)
8,760 = Number of hours in a year
T = Length of exposure (yr). "T" equals 1.45 for anodes beneath the 270° intermediate buoy, 1.65 for all other 120-lb anodes, and 5.12 for the 400-lb anode.
A = Original surface area of the anode (sq ft). "A" equals 7.5 for 120-lb anodes and 9.71 for the 400-lb anode.

5. Calculation of average current supplied to the moor: (Amp)

$$\text{Current} = \frac{500\ W_t}{8{,}760 \times T}$$

where 500 = Assumed amp-hr/lb produced by the anodes
W_t = Total weight lost by the anode(s) - (lbs)
8,760 and T are as defined in Note No. 4.

NIL resistance was measured between each anode and its conductor using a Model 260 Simpson meter.



(1) 400 LB ANODE AT END OF ANCHOR CHAIN
(2) 400 LB ANODE AT GROUND RING UNDER INTERMEDIATE BUOY
(3) SIX-60 LB ANODE STRING AT GROUND RING UNDER MAIN BUOY
(4) SIX-60 LB ANODE STRING AT FLOUNDER PLATE UNDER CENTER BUOY
(5) THREE-60 LB ANODE STRING ATTACHED TO INTERMEDIATE BUOY
(*) 17-19 NOV. 1965, REPLACED BY SIX-120 LB MAGNESIUM ANODES. 400 LB ANODES WERE LOST DURING REPLACEMENT.

Fig. 1 - Plan view of the moor in the upper sketch and a typical mooring leg elevation in the lower sketch (not to scale).

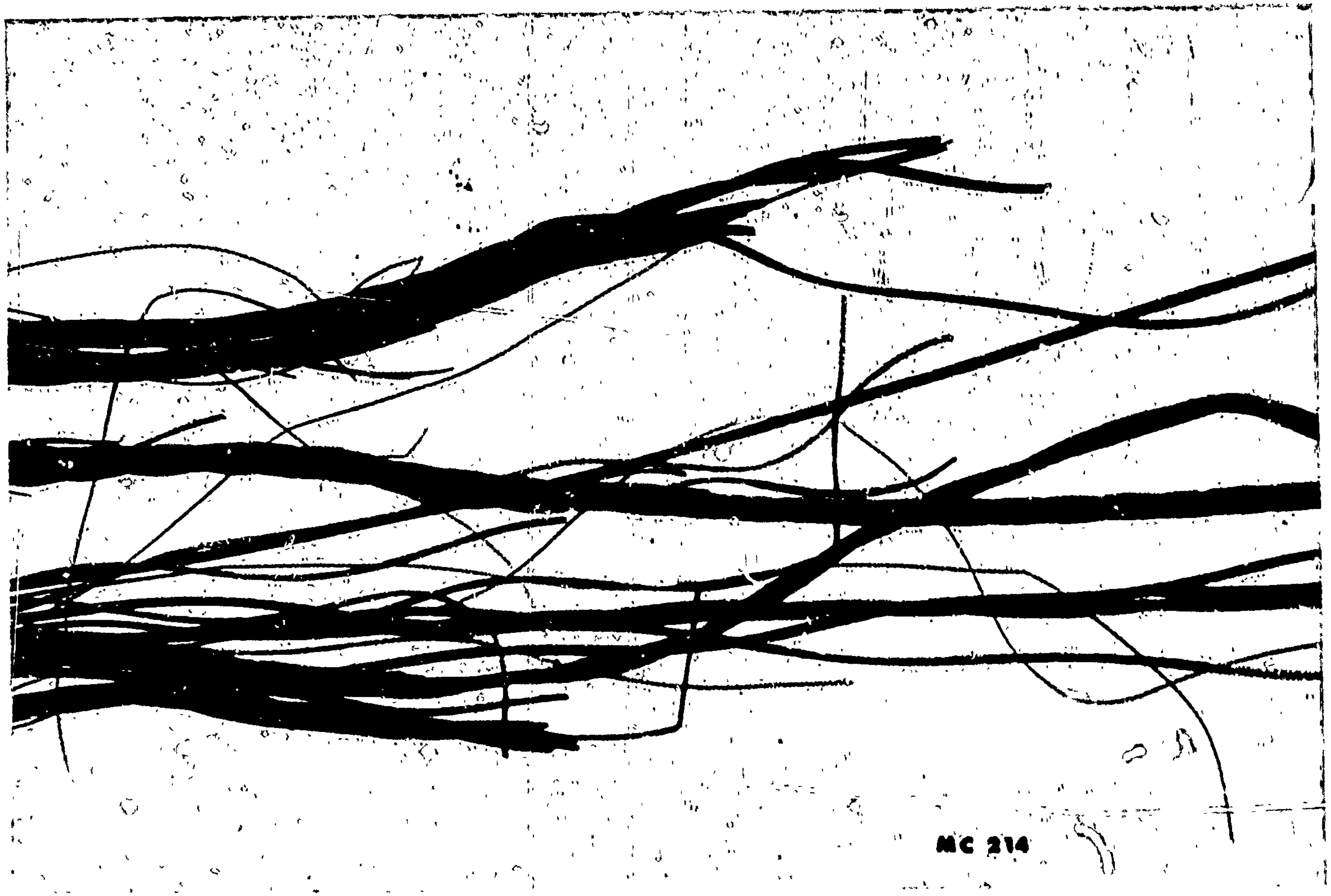


Fig. 2 - Failure of the 270° leg lower catenary 680 ft from the nearest intended anode connection. The 400 lb anode was probably lost when the moor was laid (based on relative condition of other lower catenaries). (a) The failed end of the catenary. Many outer wires are missing.

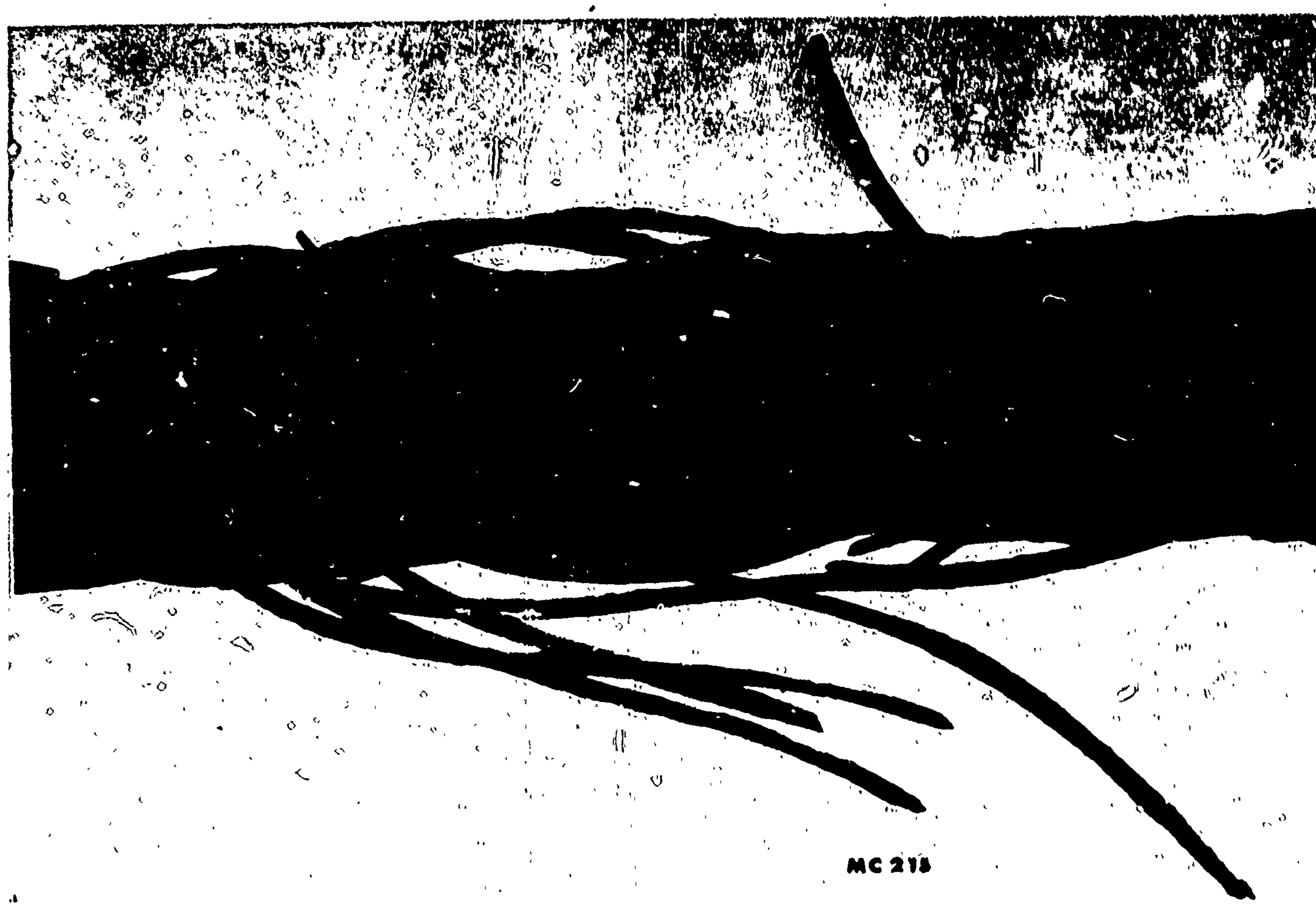


Fig. 2 (continued) - Failure of the 270° leg lower catenary 680 ft from the nearest intended anode connection. The 400 lb anode was probably lost when the moor was laid (based on relative condition of other lower catenaries). (b) Severe corrosion of the wire rope 21 ft above the failure.

Fig. 3 - Failed end of the 030° leg lower catenary 1350 ft from the nearest anode connection. Note twists and kinks; severe corrosion had not occured.

Fig. 4 - Failed end of the vertical riser 2580 ft below the 270° leg intermediate buoy or 1520 ft from nearest anode connection; severe corrosion was evident.

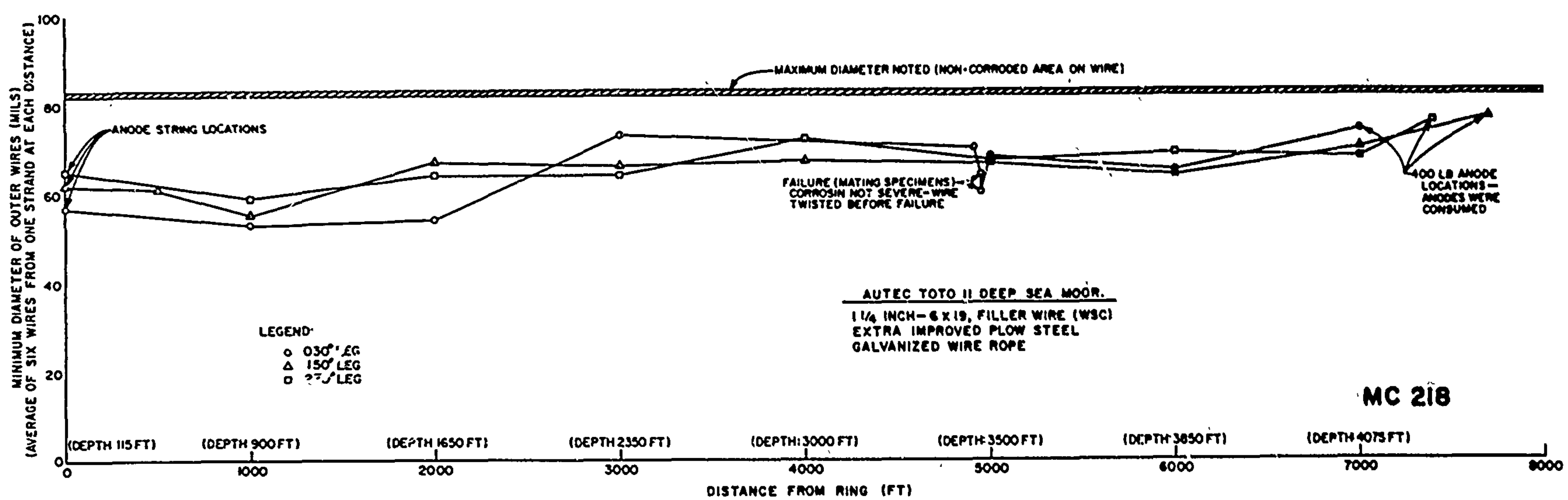


Fig. 5 - Minimum diameter of outer wires from the upper catenaries. Distances are relative to the ring located 115 ft below each main buoy as zero. Approximate depths of water are shown in parentheses.

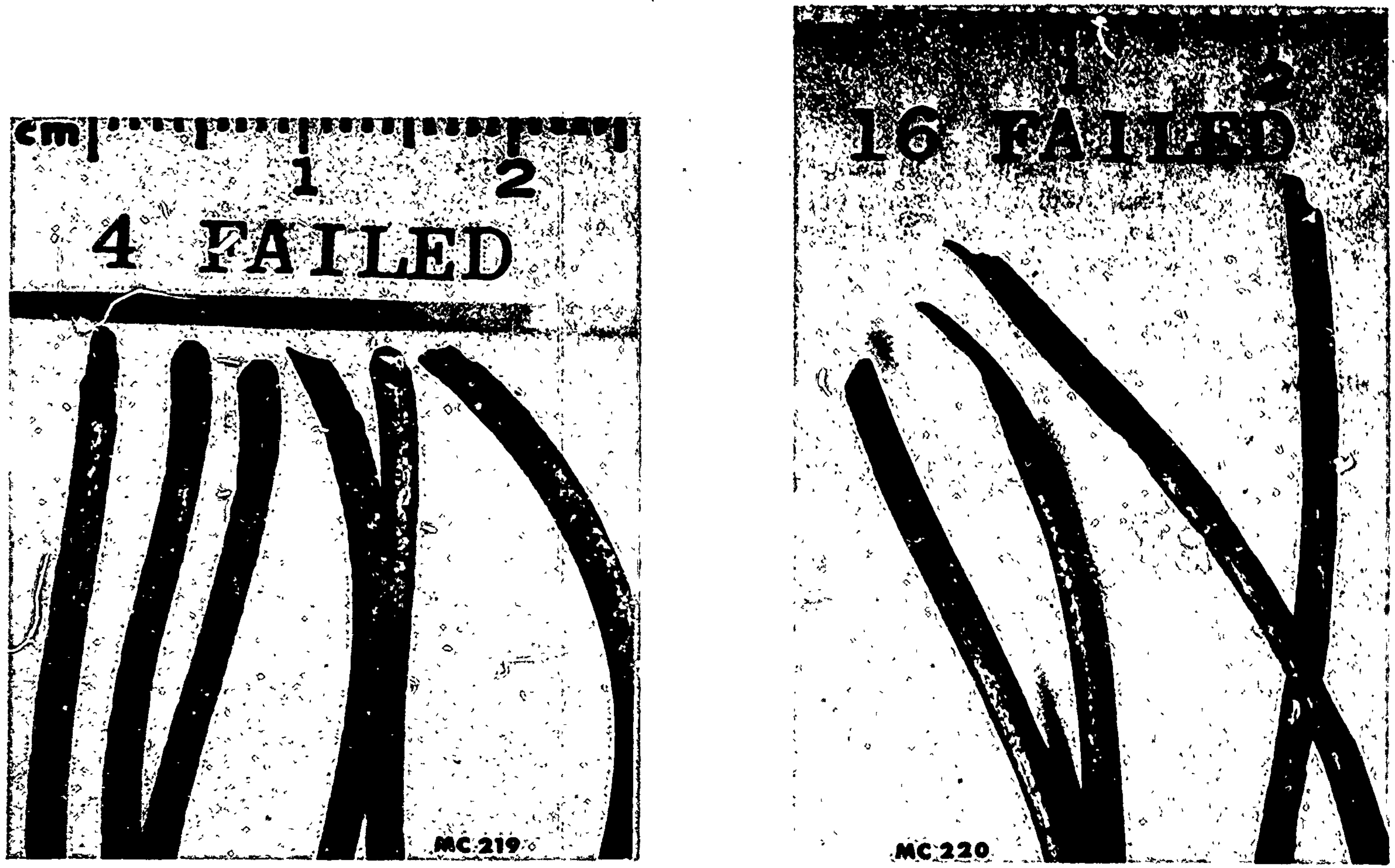


Fig. 6 – Failed ends of wires from the 030° upper catenary. Fractures on individual wires varied in appearance and wire diameters were not severely reduced.

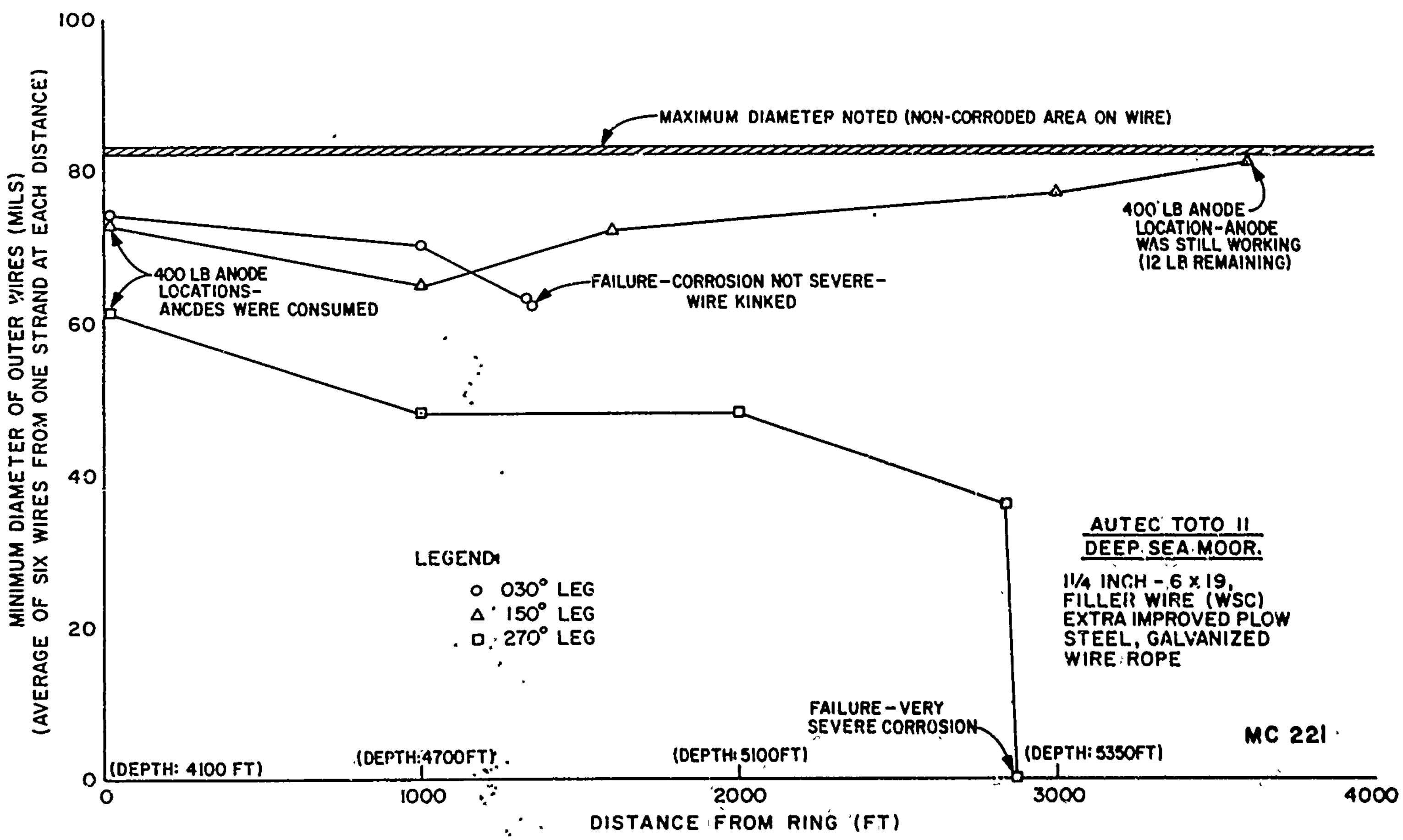


Fig. 7 – Minium diameter of outer wires from the lower catenaries. Distances are relative to the ring located about 4100 ft below each intermediate buoy as zero. Approximate depths of water are shown in parentheses.

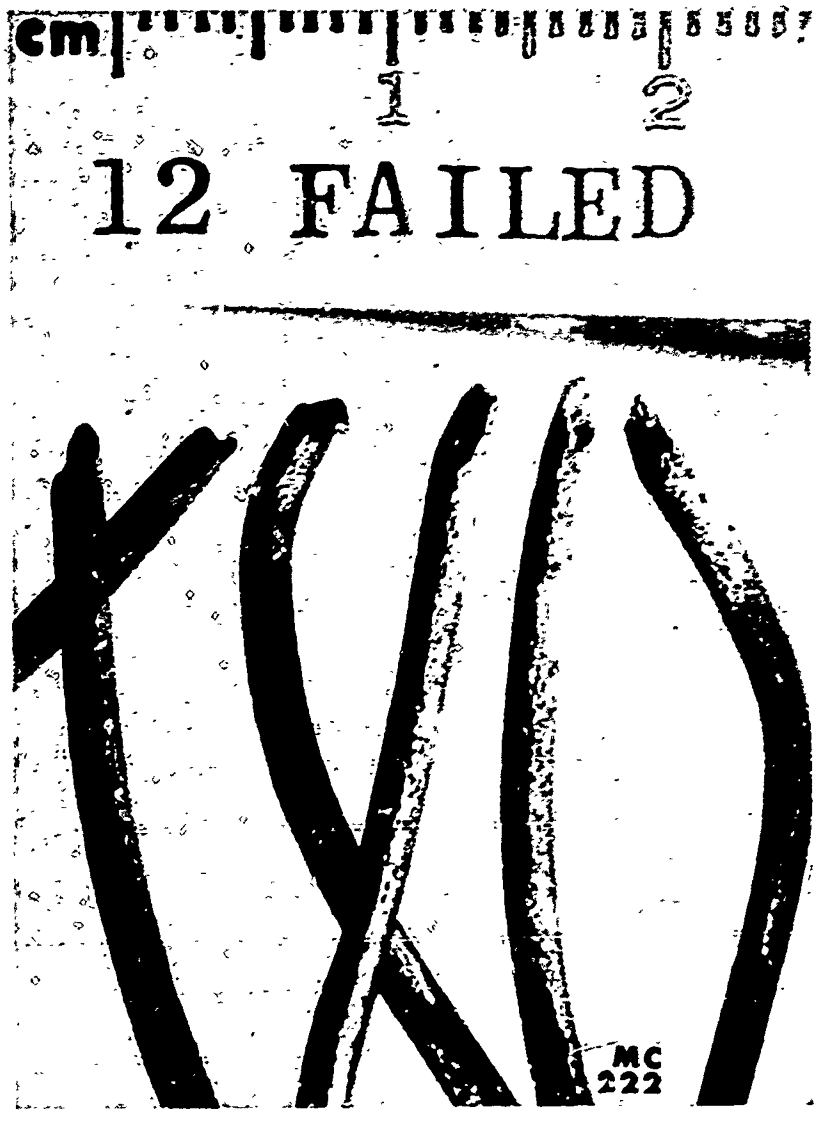


Fig. 8 – Failed ends of wire from the 030° lower catenary. The fracture appearance on individual wires varied and wire diameters were not severely reduced.

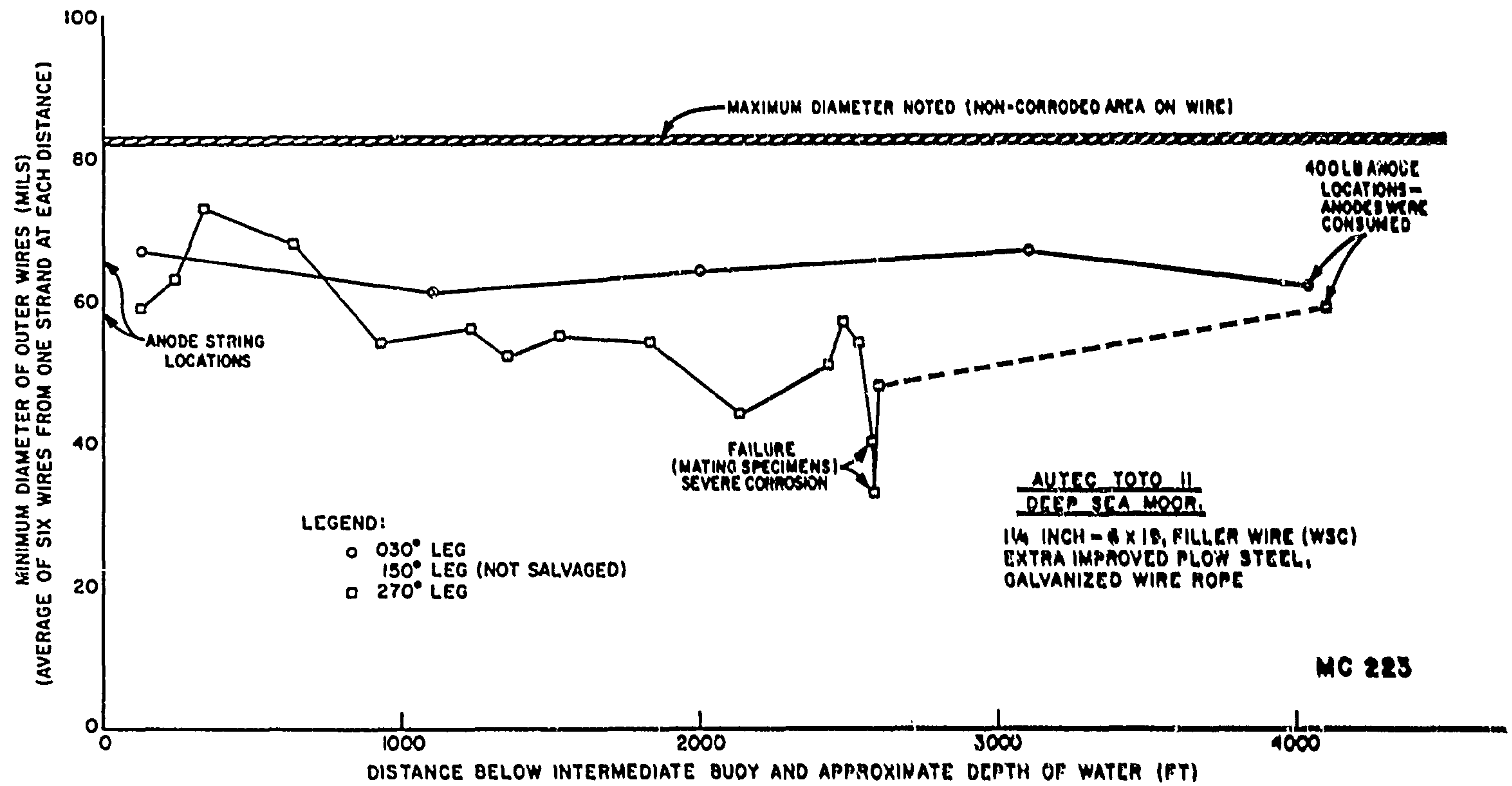


Fig. 9 - Minimum diameter of outer wires from the vertical risers beneath the intermediate buoys. Distances are relative to each intermediate buoy as zero.

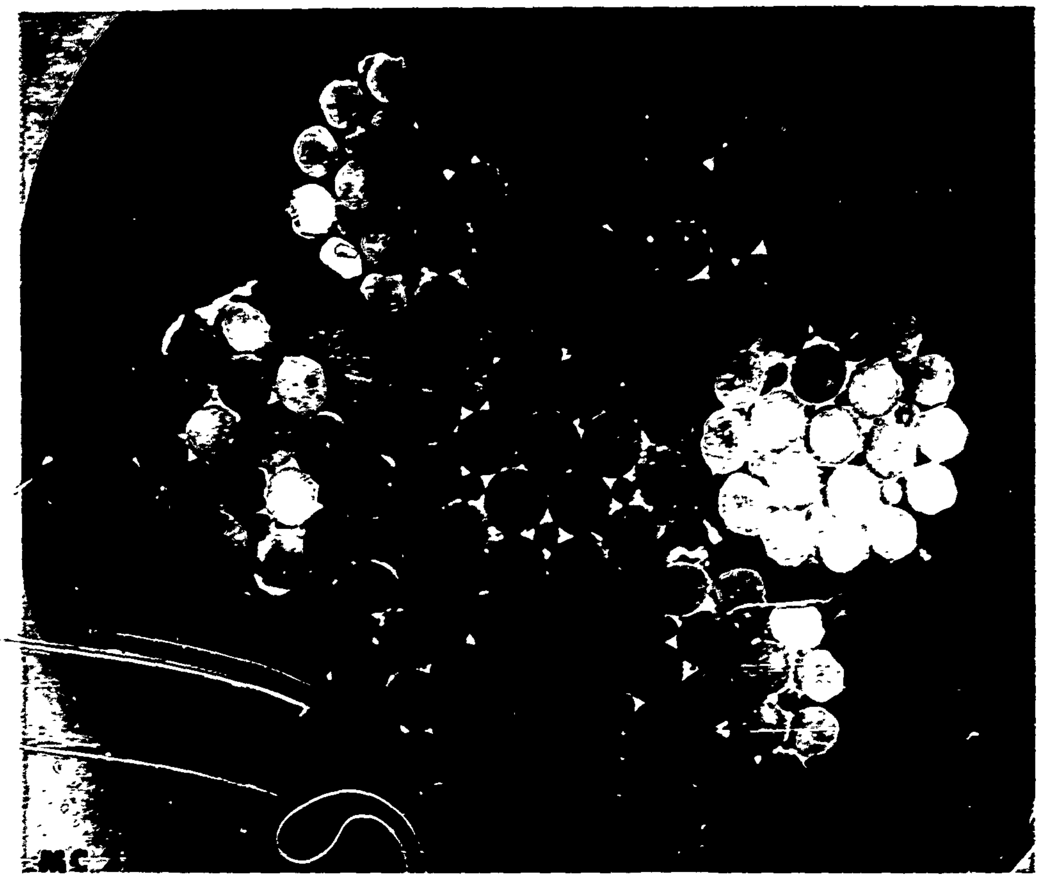


Fig. 10 - Cross section of the 270° leg intermediate buoy riser approximately 50 ft above the failure. Note the general reduction in the diameter of the outer wires on all strands. White areas on the circumference of some individual wires are residual galvanizing (zinc). Etched with 1% Nital.

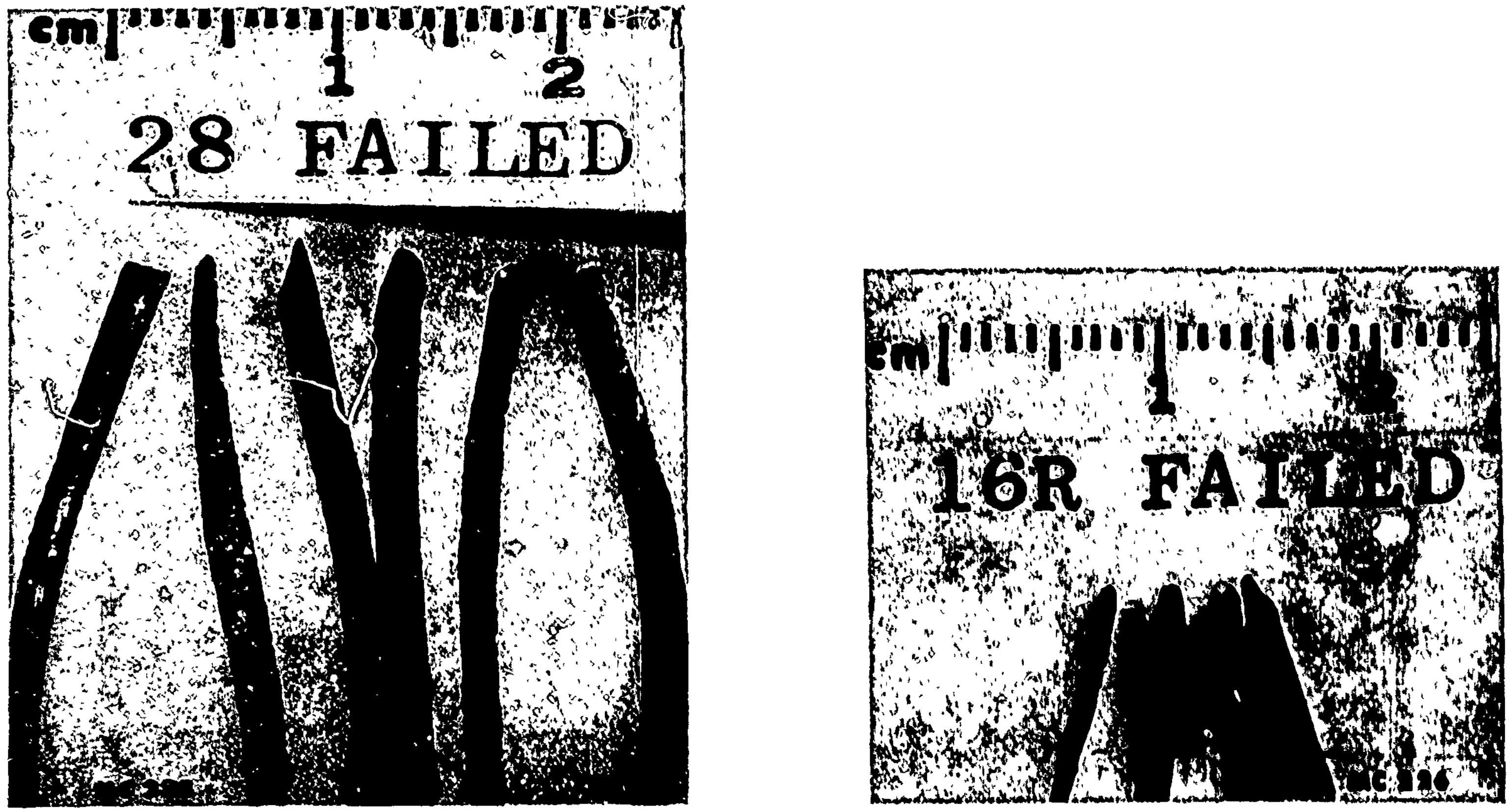


Fig. 11 - Failed ends of wires from the 270° leg intermediate buoy riser. Fracture appearance on individual wires varied and the diameter of some wires was severely reduced.

Fig. 12 - Corrosion patterns on individual magnesium anodes from the TOTO II deep sea moor. Anodes shown in (a) through (c) functioned for 1.65 years at a depth of approximately 200 ft. The anode shown in (d) functioned for 5.12 years at a depth of approximately 5400 ft.

(a) Anode 34-6; estimated current density 286 ma/sq ft.

Fig. 12 (continued) - Corrosion patterns on individual magnesium anodes from the TOTO II deep sea moor. Anodes shown in (a) through (c) functioned for 1.65 years at a depth of approximately 200 ft. The anode shown in (d) functioned for 5.12 years at a depth of approximately 5400 ft.
(b) Anode 33.6; estimated current density 342 ma/sq ft.

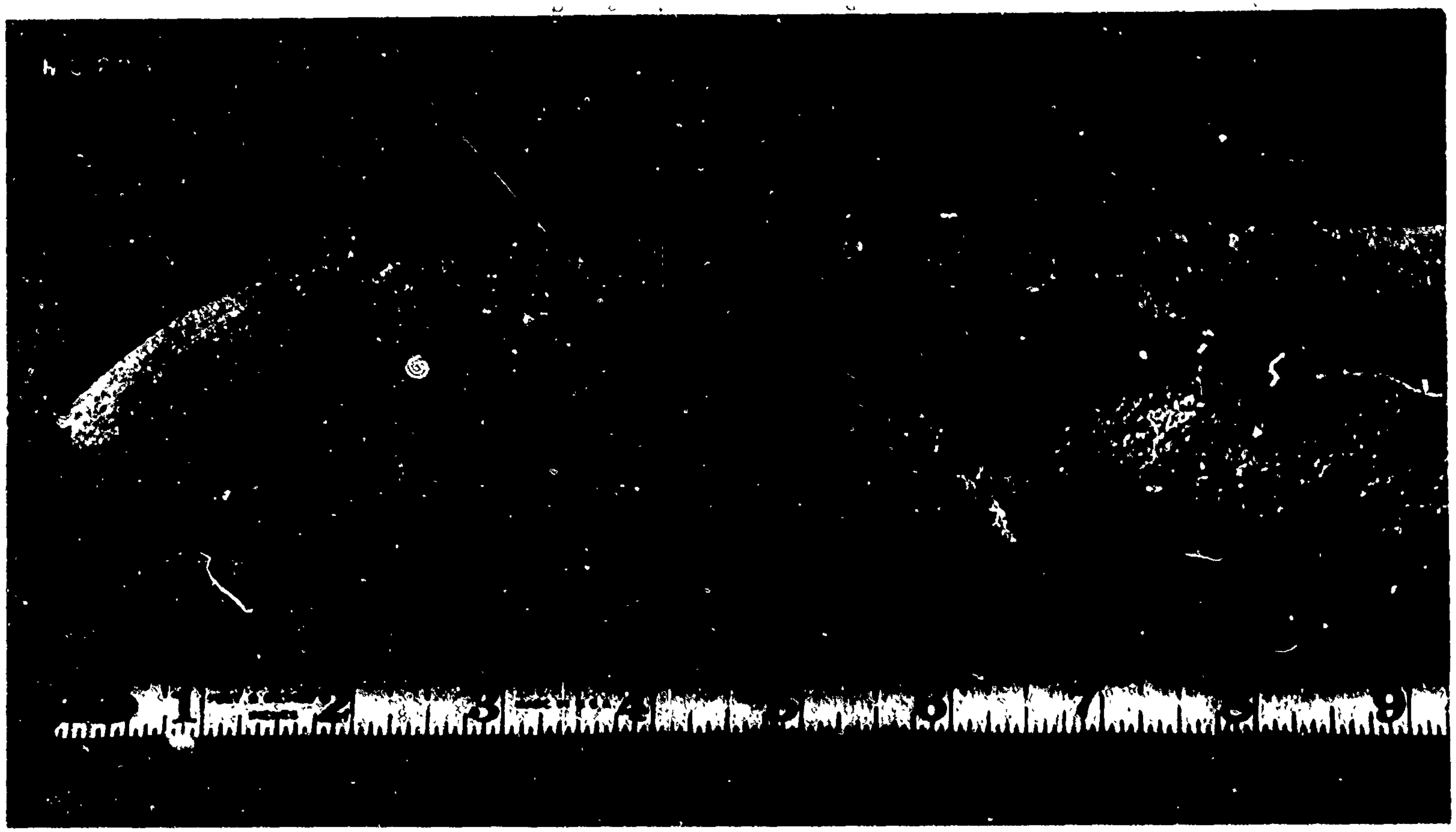


Fig. 12 (continued) - Corrosion patterns on individual magnesium anodes from the TOTO II deep sea moor. Anodes shown in (a) through (c) functioned for 1.65 years at a depth of approximately 200 ft. The anode shown in (d) functioned for 5.12 years at a depth of approximately 5400 ft.
(c) Anode 33-2; estimated current density 461 ma/sq ft.

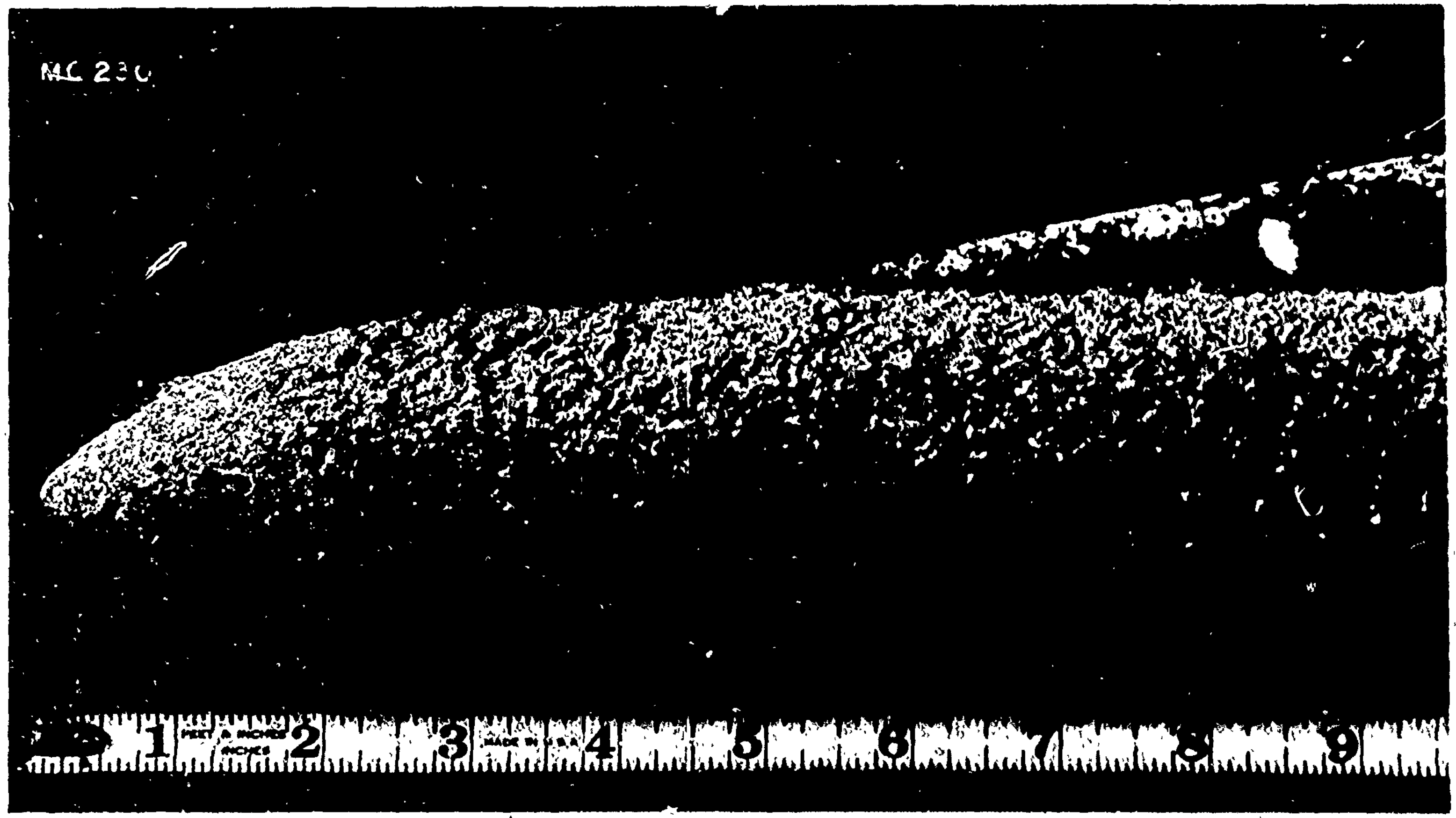


Fig. 12 (continued) - Corrosion patterns on individual magnesium anodes from the TOTO II deep sea moor. Anodes shown in (a) through (c) functioned for 1.65 years at a depth of approximately 200 ft. The anode shown in (d) functioned for 5.12 years at a depth of approximately 5400 ft.
(d) Anode 60; estimated current density 445 ma/sq ft.

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11. SUPPLEMENTARY NOTES	12. SPONSORING MILITARY ACTIVITY
	Deep Submergence Systems Project 6900 Wisconsin Avenue Chevy Chase, Maryland

13. ABSTRACT

This report contains background information on the design and installation of a wire rope three-point deep sea moor which was originally coated with a bituminous substance and the critical areas protected with a magnesium galvanic anode cathodic protection system designed by the Naval Research Laboratory. The report also describes the failure of the moor after 4 1/2 years service and its subsequent salvage, and presents the results of a study of the corrosion pattern, proposes the cause of failure, and evaluates the performance of the cathodic protection system. Recommendations are presented for the protection of future moors and for possible research directed towards the understanding and prevention of failure of wire rope structures in sea water under conditions of static stress and of fatigue.

Three of the wire rope failures were associated with severe corrosion and the absence of bituminous coating. In two of the failures the bituminous coating was essentially absent but no severe corrosion was observed. There is some circumstantial evidence that the latter failures may have been caused by a ship mooring to the intermediate buoy which was not intended to be used for this purpose. All but one failure occurred 1350 to 2050 ft from the nearest active anode connections. One failure occurred 680 ft from an intended anode connection, but there is evidence that this particular anode was lost when the moor was installed. Some other major components of the moor probably received cathodic protection for as little as 9 to 12 months out of the approximate 54-months life of the moor. This was a result of a variety of problems associated with the replacement of the original anodes.

(Continued)

14 KEY WORDS	LINK A		LINK B		LINK C	
	ROLE	WT	ROLE	WT	ROLE	WT
Deep sea moor						
AUTEC TOTO II moor						
Wire rope						
Corrosion						

The results of the corrosive attack and the failure of the moor indicate that where long life is demanded for future moors the following steps should be taken:

(a) Provide a coating better than the bituminous substance used in the present moor.

(b) Provide cathodic protection as a secondary defense against corrosion. It is essential that cathodic protection be considered early in the design phase and provided throughout the life of the moor if it is to be effective. Scheduled inspections and replacement of consumed anodes are essential for prolonged trouble-free life of the structure. Where adequate power is available, impressed current systems should be considered to obviate the necessity of frequent anode replacement.